Chapter 6. Science Objectives

A Rich and Diverse Universe

The Universe is a dynamic, evolving place—the cosmic equivalent of the web of biological and physical interactions that shape our own planet. The SEU portfolio includes missions that have revolutionized our understanding of the web of cycles of matter and energy in the Universe.

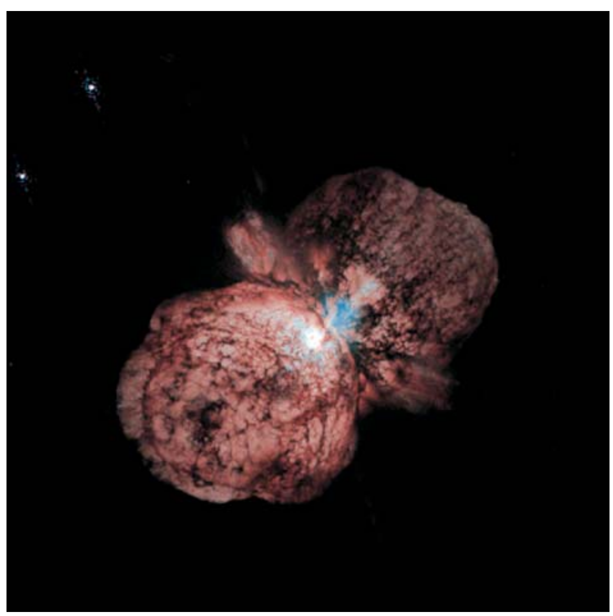
To understand the structure and evolution of the Universe, we use tools from throughout the electromagnetic spectrum to explore diverse astrophysical venues. The Chandra X-ray Observatory has been notable in this regard, opening our eyes to the richness of the X-ray Universe, as the Hubble Space Telescope has done for the optical part of the spectrum and the Space Infrared Telescope Facility will soon do for the infrared.

The Universe is governed by cycles of matter and energy, an intricate series of physical processes in which the chemical elements are formed and destroyed, and passed back and forth between stars and diffuse clouds. It is illuminated with the soft glow of nascent and quiescent stars, fierce irradiation from the most massive stars, and intense flashes of powerful photons and other high energy particles from collapsed objects. Even as the Universe relentlessly expands, gravity pulls pockets of its dark matter and other constituents together, and the energy of their collapse and the resulting nucleosynthesis later work to fling them apart once again.

The aim of the SEU theme is to understand these cycles and how they created the conditions for our own existence. To understand how matter and energy are exchanged between stars and the interstellar medium, we must study winds, jets, and explosive events.

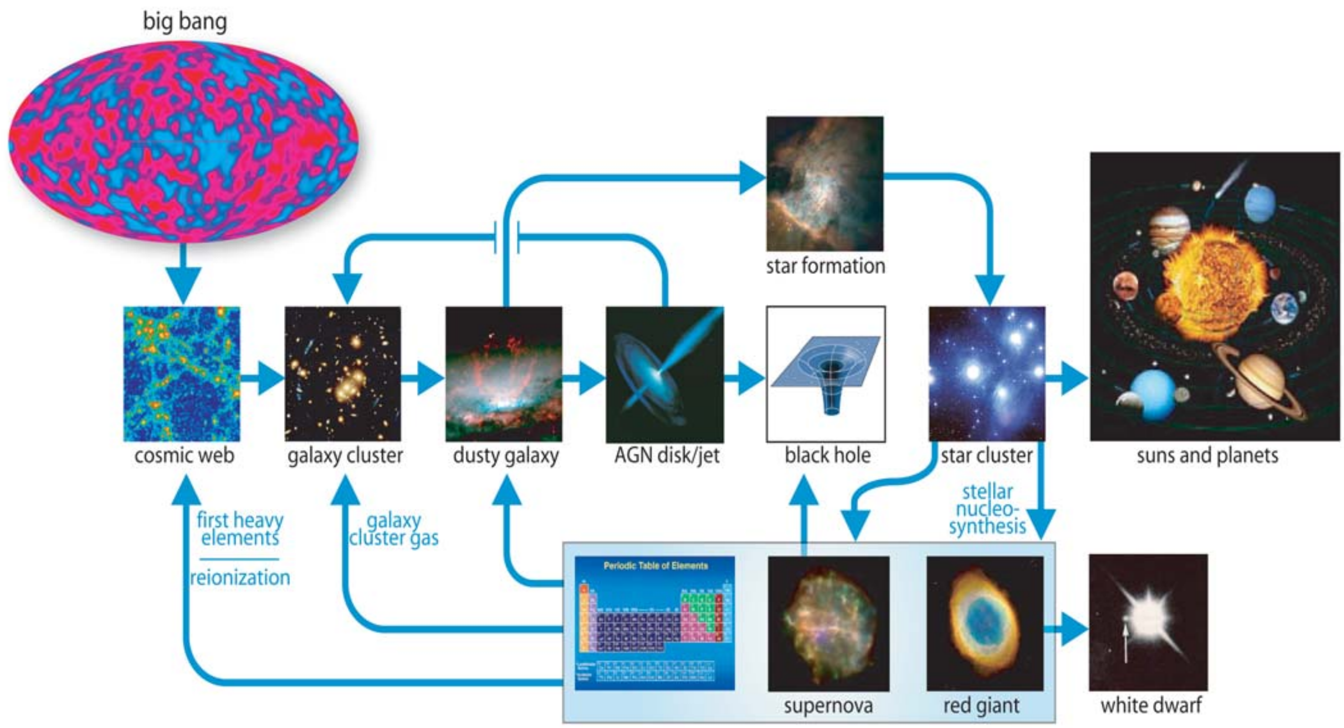
"All of us are truly and literally a little bit of stardust."
—William A. Fowler [Nobel Prize, 1983]

From gas to stars and back again . . .



A huge, billowing pair of gas and dust clouds is captured in this Hubble telescope picture of the super-massive star Eta Carinae. Eta Carinae suffered a giant outburst about 150 years ago and now returns processed material to the interstellar medium.

SEU CYCLES OF MATTER AND ENERGY



Interdependent cycles of matter and energy determine the contents of the Universe. The aim of the SEU theme is to understand these cycles and how they created the conditions for our own existence.

Our task includes uncovering the processes that lead to the formation of galaxies and their dark matter halos. Finally, we seek to understand the behavior of matter in extreme environments: crushing neutron stars, the sources of gamma-ray bursts, and the highest-energy cosmic rays.

The missions of *Beyond Einstein* can address some of the goals of the *Cycles of Matter and Energy* program. But to unravel the interlinked cycles, future missions with additional capabilities are needed.

- To decipher the flows of gas and energy in the first galaxies: a cryogenic, large aperture infrared observatory.
- To uncover how supernovae and other stellar explosions work to create the elements: an advanced Compton telescope and a hard-X-ray spectroscopic imager.
- To map the “invisible” Universe of dark matter and gas expelled during the birth of galaxies: a large-aperture telescope for imaging and spectroscopy of optical and ultraviolet light.
- To measure the motions of the hottest and coldest gas around black holes: a radio interferometer in space.

- To see the birth of the first black holes and their effect on the formation of galaxies, and to probe the behavior of matter in extreme environments: a very large aperture arc-second X-ray imaging telescope.
- To determine the nature and origin of the most energetic particles in the Universe today: a mission to track them through their collisions with the Earth.

What We Have Learned

The cycles that we seek to understand are driven by stars and galaxies. Before describing how we plan to proceed, we briefly review what we have learned so far about these, the principal actors.

Stars: Engines of Change in an Evolving Universe

Stars are the factories for new elements in the Universe and, by the energy that they deposit there, mix the raw material for succeeding generations. The SEU theme is committed to mapping the processes by which these stellar factories build up the Universe.

For a star, mass is destiny—the low mass stars slowly fuse hydrogen into helium, while massive stars burn fiercely for a brief cosmic moment. Stars about one-half the Sun's mass or less have a lifetime that is at least as long as the present age of the Universe. The oldest of these stars show us that our Galaxy once lacked the heavy elements out of which planets and people are made. Stars of later generations, like the Sun, inherit a legacy of atoms created by short-lived massive stars when the Universe was young.

Massive stars create new elements—oxygen, calcium, iron—and return them to space through stellar winds. At the end of these stars' lives, fierce fires forge elements heavier than iron and expel them in the huge explosions called supernovae. The accumulated products of these events become the material for new stars that form in the densest interstellar regions, and which also serve as cradles for organic molecules related to life. Lower-mass stars evolve more sedately. As they run out of hydrogen fuel, they slowly expand to become large, cool "red giant" stars. These stars exude strong "stellar winds" that are the major source for interstellar carbon, oxygen, and nitrogen. Our Earth, and our bodies, are formed from the chemically processed ejecta of all these stars.

Galaxies: Bringing it all Together

These stars congregate, by the billions, in billions of galaxies, which come in a wide range of sizes and shapes. To explain this rich variety, SEU missions will trace their evolution from their origins in the early Universe to the intricate systems we find today.

We know that when the Universe was a much younger and more violent place, super-massive black holes were gorging themselves in a natal feeding frenzy as galaxies formed around them. The signposts of this process are the quasars

Fountains of new elements spraying into the Universe . . .

This HST snapshot of the galaxy NGC3079 reveals dramatic activities in its core. Gaseous filaments at the top of a hot bubble of gas are being expelled into intergalactic space. Eventually, some of this gas will rain down on the disk to form new generations of enriched stars.

National Priorities. The National Academy of Sciences decadal survey *Astronomy and Astrophysics in the New Millennium* (Astronomy and Astrophysics Survey Committee, 2001) has endorsed several missions that support the science objectives of Cycles of Matter and Energy. These missions are the Gamma Ray Large Area Telescope (GLAST), the Single Aperture Far Infrared (SAFIR) observatory, the international Advanced Radio Interferometer between Space and Earth (ARISE), and the Advanced Cosmic-ray Composition Experiment for Space Station (ACCESS). The survey has also endorsed the Ultra Long Duration Balloon (ULDB) program, the laboratory astrophysics program, and the theory program.

and active galactic nuclei. Even relatively quiet galaxies like our own have massive black holes lurking at their centers. What role did black holes play in the evolution of galaxies?

It is a daunting challenge to try to understand events that happened billions of years ago in faraway places. But we can do this in at least three ways. We can measure the ages of stars in nearby galaxies to reveal their history of stellar births. We can study nearby galaxies still under construction today. And we can use powerful telescopes as time-machines to see the past directly: as we peer farther out into space, we see back in time.

The Next Steps: The Space Astronomy Imperative

Space-based telescopes are uniquely suited to uncovering the cycles of matter and energy in stars and galaxies. Different parts of these cycles produce radiation of different wavelengths. On Earth, we are restricted to peering at the cosmos in the narrow ranges of wavelength that our atmosphere happens to let through. From space, we can choose our observation wavelengths based on their information content. The isolation of a space satellite also allows more stable and precise pointing, giving the clearest view of the Universe. It also allows for cooling the telescopes, which can vastly increase the sensitivity at some wavelengths.

Of New Stars and New Galaxies

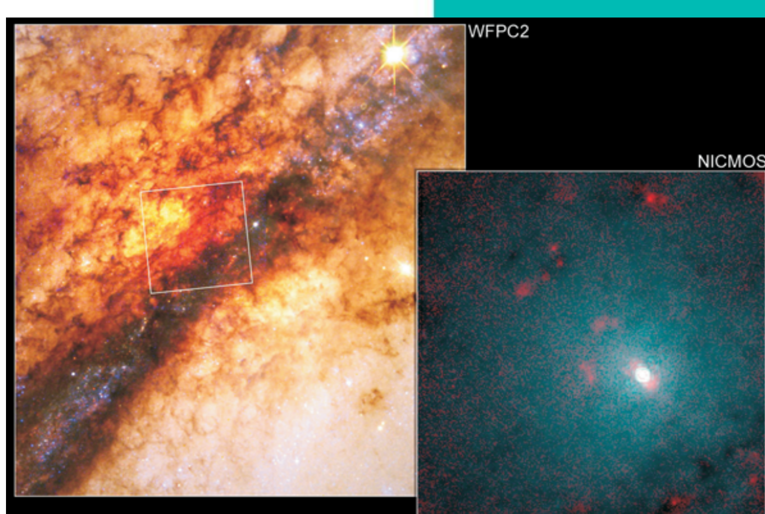
We are just beginning to learn how star formation takes place locally, enabling us to look for its signatures in the distant Universe. The Stratospheric Observatory for Infrared Astronomy (SOFIA) and new space observatories such as the Space Infrared Telescope Facility (SIRTF) and ESA's Herschel Space Observatory will make these first attempts.

active galactic nuclei

dusty galaxies

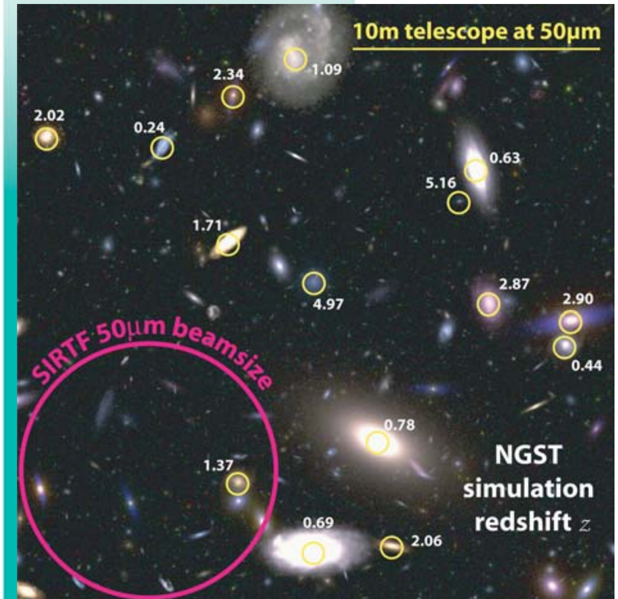
supernovae

'Twould be lonely,
'twould indeed,
If the night were
void of stars.
—G.O. Pitcovich
(from If the Night Were Void of Stars.)



Glimmers of secrets through the murk . . .

The infrared transparency of a nearby dust enshrouded galaxy (Cen A) is illustrated by comparing an HST optical image (left) with a near infrared NICMOS image of the nuclear region (inset at right). The center of this galaxy is clearly revealed at infrared wavelengths.



Details of a distant youth . . .

The infrared acuity of a space-based 10-meter far-infrared telescope (small yellow circles) is superimposed on a simulated JWST image of distant extragalactic targets. The large red circle shows that of NASA's SIRTF (a 0.85 m telescope), which is too poor to distinguish individual distant galaxies. The larger telescope will be able to pick out newly born galaxies at the edge of the Universe.

The Big Bang created only the lightest two elements, hydrogen and helium (plus tiny traces of lithium and beryllium). So the first generation of stars formed in warm, dense clouds containing just those two elements. These clouds cooled because hydrogen molecules radiated their heat—at infrared wavelengths that can only be seen from space. A cryogenic, large aperture infrared telescope would be able to see these molecular lines, and offer a unique window into early star formation. Such a single aperture far-infrared (SAFIR) mission could build upon James Webb Space Telescope (JWST) technology.

The plan for the SEU theme takes three concerted approaches—cosmic censuses, looking at the Universe long ago and far away, and understanding contemporary mechanisms of galaxy building.

The first solid particles, "dust," condensed from the heavier elements created by the first generations of stars. This was a key event. The dust absorbed light and protected subsequent stellar nurseries from the damaging effects of ultraviolet light. The dust hides these nurseries from optical and ultraviolet instruments but is transparent to the infrared light that the dust emits. For the farthest sources, most of this emission is shifted to wavelengths that are inaccessible from the ground. For this reason, far-infrared and submillimeter telescopes in space should find these distant sources to be almost as bright as more nearby sources, making such telescopes powerful cosmological tools.

The carbon, nitrogen, and oxygen created by the first stars radiate in bright emission lines from the infrared through X rays. We can use these spectral lines to measure redshifts and diagnose the radiating gas. The radiation in these lines rapidly cooled the interstellar clouds, leading to even more star formation.

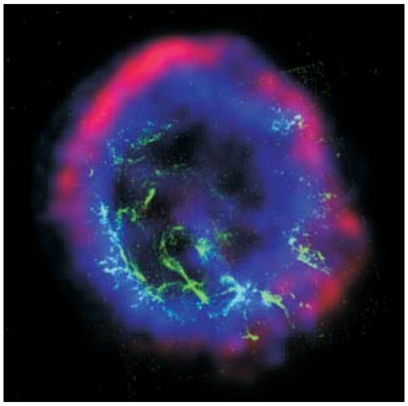
With high spectral resolution these lines can be used to trace the flows of this gas in detail. Most of the line radiation that cools collapsing gas clouds is not accessible to ground-based investments such as the Atacama Large Millimeter Array (ALMA). Cryogenic single-dish space telescopes will provide direct measurements of these lines and, with new large format arrays, be vastly more effective for deep surveys. Submillimeter interferometers in space will eventually offer detailed images, complementing the huge increases in sensitivity that single-dish instruments will provide.

The Explosive Enrichment of Galaxies

The structure and evolution of the Universe is strongly driven by stellar collapse and explosive events, which inject the energy and the elements essential to life into the interstellar gas. To understand the consequences, we need new tools to measure the rates of injection.

Supernovae bright enough to observe directly are relatively rare. But the rapidly expanding remnants they leave behind slowly cool and mix with the surrounding interstellar medium, revealing its composition for centuries afterward. Metals such as gold and

Visions of new elements from a cosmic furnace . . .



A color composite of the supernova remnant E0102-72: X-ray (blue), optical (green), and radio (red). E0102-72 is the remnant of a star that exploded in a nearby galaxy known as the Small Magellanic Cloud. The Chandra X-ray Observatory image shows, in blue, gas that has been heated to millions of degrees Celsius by the rebounding, or reverse shock wave. The X-ray data show that this gas is rich in oxygen and neon. These elements were created by nuclear reactions inside the star and hurled into space by the supernova.

silver are signatures of the supernova explosion process itself. Most of the material of supernova remnants shines brightly with X-ray lines and Constellation-X will play an important role in determining their makeup: Cosmic rays provide another sample of material from the vicinity of supernova explosions.

Radioactive elements are formed in detonation and core collapse supernovae, during nuclear burning on white dwarf novae, and in the inner accretion disks of neutron stars and black holes. An advanced Compton telescope that can see the radiation from these radioactive decays can be used to study the explosion mechanisms in core-collapse supernovae. While pioneering efforts have come out of the Compton Gamma Ray Observatory, and will be strengthened by ESA's INTEGRAL, a dramatic improvement in sensitivity is required to study more than a few supernovae and to make measurements on a time scale shorter than the decay lifetimes of the key isotopes. Recent technical advances offer increased sensitivity, lower background, and improved energy resolution.

Gamma-ray line telescopes will also help studies of classical novae, in which hydrogen-rich material from a close companion is more delicately deposited on a white dwarf, inducing a localized thermonuclear runaway. Even in these smaller explosions, short-lived isotopes of light elements are produced and should be detectable over much of the galaxy.

Studies of gamma-ray bursts (GRBs) have produced some of the most striking science of the last decade. The Compton Observatory established that GRBs were uniform over the sky. The European Beppo-SAX mission identified optical afterglows that demonstrated that GRBs are extragalactic in origin. As a result, these bursts are now understood to outshine, for minutes at a time, the galaxies in which they originate. Those that last longer than about one second are most likely associated with massive stars and core-collapse supernovae. While the statistics are still sparse, future survey missions such as Swift and GLAST will dramatically enhance the sample.

Some gamma-ray bursts signal the death of a star and the birth of a black hole. Others may arise when a star is swallowed by a nearby black hole. The bursts are so bright that they can be seen even from the distant, early generations of stars. A wide-field, high-sensitivity advanced Compton telescope, and the Black Hole Finder Probe from the *Beyond Einstein* program, will search for dim GRBs, both nearby and distant. Ground-based and space-based optical follow-up studies will supplement these efforts, providing redshifts and identifying the host galaxy.

active galactic nuclei

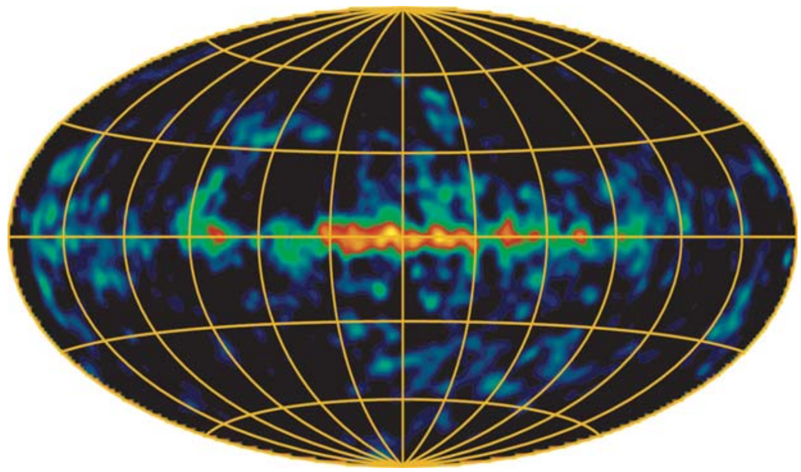
dusty galaxies

supernovae

Seeing the earliest stars in the earliest galaxies is now within our technological reach. We will build telescopes that will do this, and efficiently detect and assay interstellar gas out of which these stars are made.

Future telescopes will let us see nucleosynthesis happen, and chart how the Universe gets seeded with the materials out of which we are made.

Glowing embers of galactic nucleosynthesis . . .

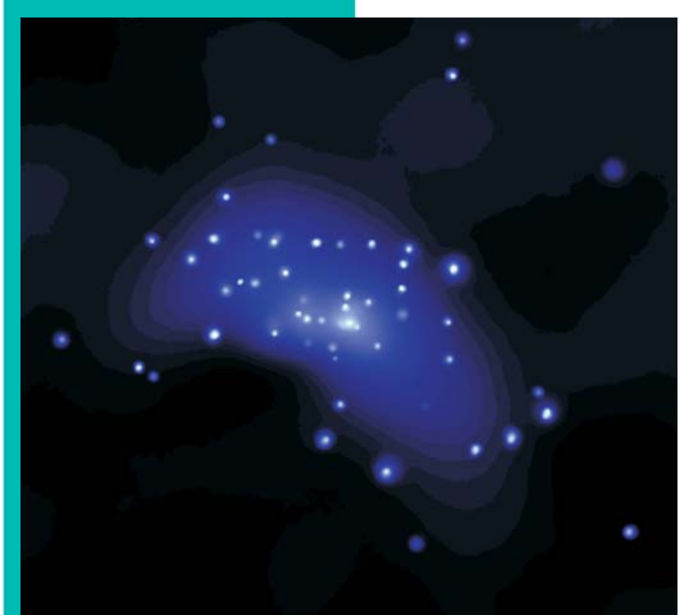


In this wide angle 1.809 MeV gamma-ray view of the Milky Way Galaxy from NASA's Compton Gamma -Ray Observatory, bright spots made by radioactive ^{26}Al show clearly. With a half-life of about a million years—short compared with the timescale of nucleosynthesis—the bright spots that concentrate in the inner galaxy must be contemporary sites of elemental enrichment.

Light and Wind from the Heart of the Beasts

Beyond Einstein focuses on the physics of spacetime around compact objects and in the early Universe. Compact objects—white dwarfs, neutron stars, and black holes—are the endpoints of stellar evolution. Their physics determines how energy and matter are deposited throughout the Universe, and they play an important role in its structure and evolution. These objects also allow observational access to extremes of density, pressure, temperature, and magnetic field energy. Neutron stars offer extraordinary densities of matter and magnetic field strengths. Unique processes, including coherent synchrotron emission from pair cascades and the magnetic-field conversion of gamma rays to electron-positron pairs, take place near these objects. These cosmic laboratories test physics under extreme conditions that we cannot reproduce on Earth.

Compact objects can be probed in many ways. A cooling neutron star appears as a hot object in X-rays. Neutron stars



Revealing gravitational rogues inside galaxies . . .

The Chandra X-ray Observatory's image of the galaxy NGC 4697 reveals diffuse hot gas dotted with many point-like sources, which are due to black holes and neutron stars in binary star systems. The bright central source is probably due to a supermassive black hole in the nucleus of the galaxy.

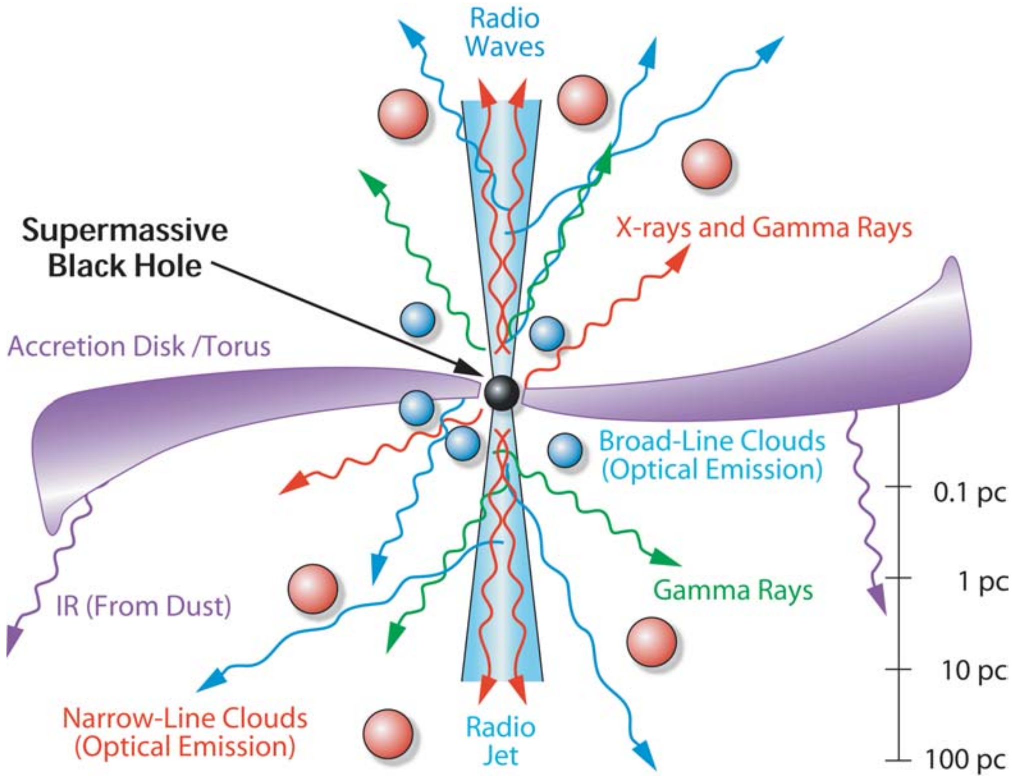
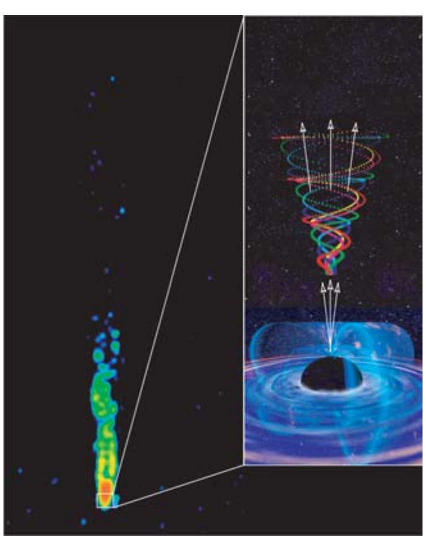


Diagram of AGN with warped disk. Note nonlinear scale; 1pc = 3.3 light years.

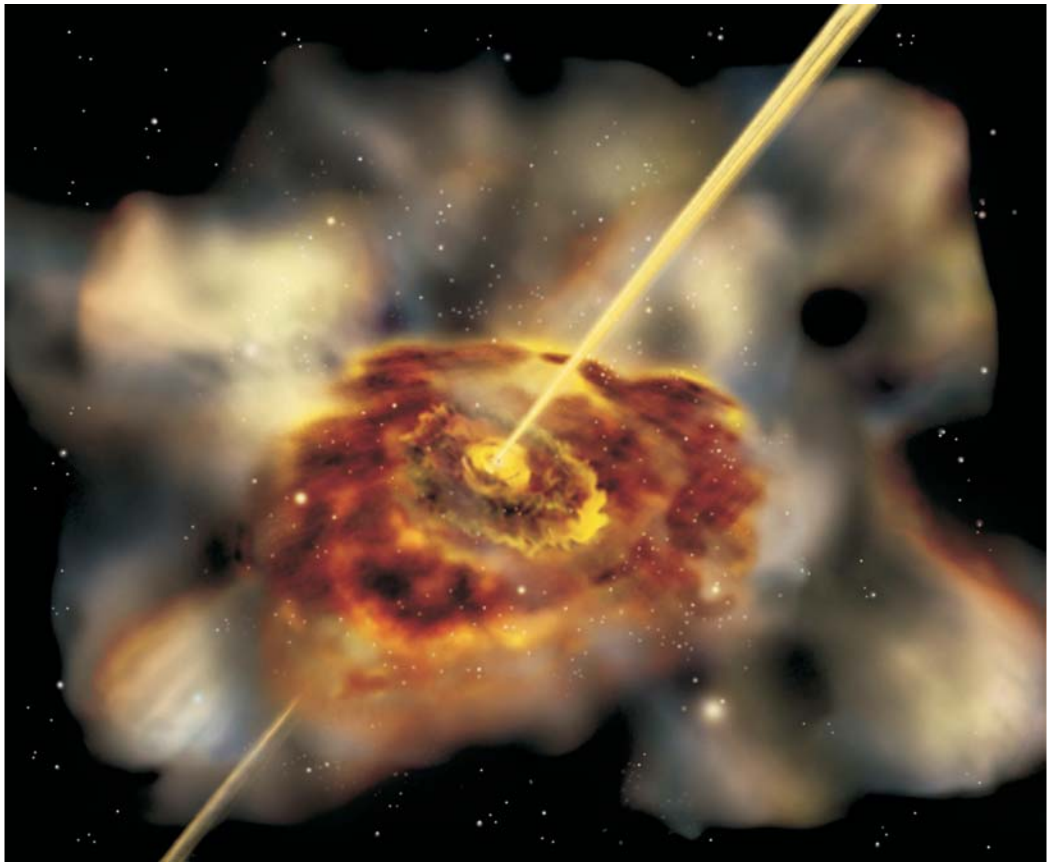
cool over a few thousand years, and their cooling rate and spectra provide information about the neutron star interior. Matter falling onto a neutron star from a binary companion also heats up and can ignite in thermonuclear explosions. Oscillations in the X-ray emission of compact objects reveal instabilities in the accretion disk and even the underlying

Firing celestial beams of matter . . .



The large improvement in spatial resolution of space radio interferometry over that from the ground allows the inner parts of nearby galactic accretion disks, and even event horizons of nearby black holes to be probed. At left is a VLA image of the jet flowing out of the supermassive black hole in the galaxy NGC4158. At right, an artist's conception of the launch region of the jet, with the event horizon of the black hole at center. It is this vastly smaller scale that space interferometry will probe.

Peering into the hearts of galaxies, we will use new telescopes to study the powerful flows of matter and radiation that emanate from the massive black holes at their cores.



Swirling disks of death around black holes . . .
In this artist rendering, gas spirals into an accretion disk around a supermassive black hole at the core of a galaxy. The gravitational energy liberated by the infall causes the central region of the disk to become fiercely luminous and it drives a jet of material outward along the polar axes of the galaxy.

physics of the hidden neutron-star interior. Compact object studies reveal the activity of high-mass stars that produce the heavy elements required for life to form.

In recent years, NASA missions such as the Chandra X-ray Observatory and the Compton Gamma Ray Observatory (CGRO) have shown that gas falls onto compact objects via accretion disks. As the gas falls in, it heats up and emits powerful radiation that can be seen by high-energy telescopes, or indirectly with infrared and radio telescopes.

These nuclear furnaces are often shrouded by the very dust and gas that provides the fuel for the beast. The veil can be penetrated by infrared, radio, and X-ray, or gamma radiation. The Gamma-ray Large Area Space Telescope (GLAST), now in development, will see the most energetic regions around black holes. The Black Hole Finder Probe from *Beyond Einstein* will take a census of nearby black holes. These studies will help us pin down the role black holes have played in the development of galaxies.

Quasars are active galactic nuclei (AGN) so bright that they outshine the surrounding galaxy. The evidence suggests that their radiation is produced by a supermassive black hole ingesting material from the galaxy surrounding it. Because of their high luminosities, AGNs can be seen at very great distances, providing fundamental information about

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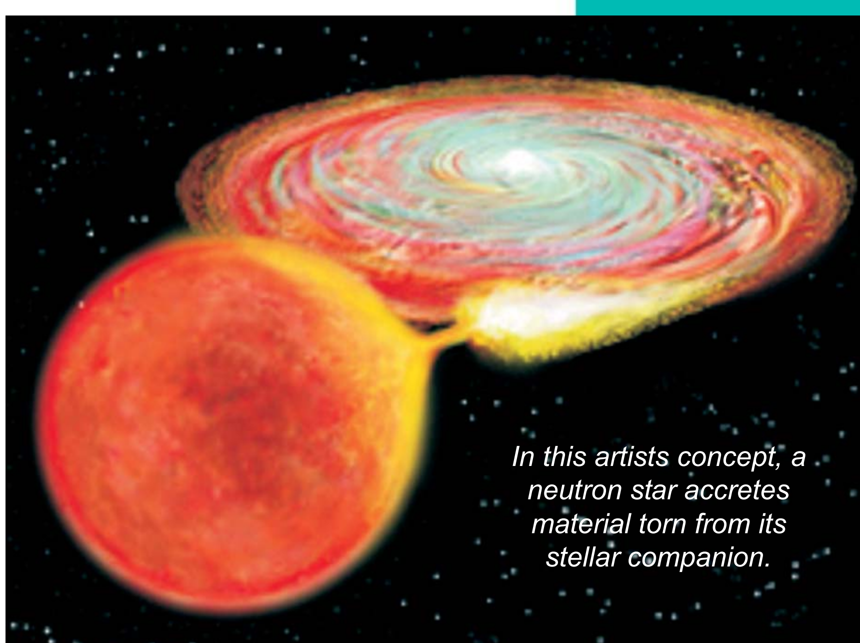
the era when AGN were far more common and the Universe was only 20 percent of its present age. The James Webb Space Telescope (JWST) and a more powerful successor to HST could be used to study AGN during this epoch.

Did supermassive black holes form by merger of smaller ones, were they massive when they first formed, or did they grow by eating their galaxies from the inside? The Chandra X-ray Observatory has detected supermassive black holes out to $z = 5$, long before most stars were formed. LISA and JWST will measure the properties of even more distant black holes. Constellation-X will study these galaxies in spectroscopic detail, determining their composition and the rate at which they are being devoured by their central black holes. Such observations would help us design an eventual vision mission that could see even quiet galaxies at great distances and round out our picture of galaxy formation.

Since the accretion disk is the supplier of fuel for compact objects, better understanding of these objects will require us to figure out how the disks collect matter and funnel it into the central hole. New instruments from the *Beyond Einstein* program will help us study the innermost parts of the accretion disks of supermassive black holes.

Accretion disks are also studied on larger scales using ground-based very long baseline interferometry (VLBI). This can map radio-emitting material in the accretion disk with a resolution over a hundred times finer than HST gets at visible wavelengths. Recent VLBI maps of AGN have detected intense maser emission from water molecules. This emission arises in the cool, outer parts of the accretion disk and has made it possible to measure the masses of several nearby supermassive black holes with unprecedented accuracy.

The full power of radio interferometry will not be realized until space-based telescopes provide longer baselines and shorter wavelengths. Molecular maser lines would offer information about mass motions in the cooler, outermost part of the disk. A radio interferometry mission would resolve accretion disks around AGN out to almost 200 Mpc and probe the inner disk that surrounds the closest supermassive black hole, in the galaxy M87. Such measurements would supplement the more complete dynamical picture provided by Constellation-X and the vision mission Black Hole Imager.



In this artists concept, a neutron star accretes material torn from its stellar companion.

Of special interest is the black hole that sits quietly at the center of our own Milky Way galaxy. As the closest massive black hole, it offers special opportunities. While it now seems to be accreting little matter, a more exciting recent history may be reflected in the motions of nearby material. Though hidden from optical view by the disk of our Galaxy, this material is accessible to us at radio, infrared, and X-ray wavelengths.

Accretion disks around black holes often produce powerful "jets" along their polar axes, which effectively clear away the raw materials of star formation in these directions. Understanding how these jets are made, and what role they play in the accretion process, is a major unsolved problem. While jets have now been observed throughout the electromagnetic spectrum, new telescopes with vastly increased sensitivity, spectral resolution, and clarity of view such as Constellation-X will permit a coordinated attack on gas flows in these disks, and the acceleration mechanisms by which the jets—truly cosmic cannons—are formed.

Detailed comparison of star formation in galaxies with active nuclei will be needed to investigate the roles that accretion disk-driven winds and point-like gravitational fields have on the formation of stars and the evolution of galaxies.

Understanding Nature's Flash Bulbs to Measure the Universe

We are ready to understand how the standard candles burn, lighting our way to the early Universe.

Supernovae play a profoundly important role in the chemical enrichment of the Universe. But they can also help us measure it! Type Ia supernovae are uniquely important in this regard because they are very bright and have roughly constant peak brightness. These cosmic flash bulbs can thus be used to measure the large scale geometry of the Universe. An intensive hunt for such supernovae is under way and early results have led to the monumental realization that the expansion of our Universe is accelerating. While Type Ia supernovae (SN Ia) appear to be ideal for this kind of work, and provide a possible basis for the Dark Energy Probe of the *Beyond Einstein* program, their utility as a standard candle ultimately rests on our detailed understanding of their nature. They most likely arise from the detonation of a white dwarf that pulls so much mass off of a nearby companion that it collapses, triggering an explosive thermonuclear burn. But we cannot understand the evolution of their properties over cosmic times without modeling their nuclear burning and dynamics.

A supernova of Type Ia can eject large quantities of newly formed radioisotopes. These can be identified by their characteristic gamma-ray emission lines. By observing and modeling this radiation, missions such as an advanced Compton telescope and a hard X-ray spectroscopic imager will provide a solid basis for the use of Type Ia supernovae as a probe of cosmology. Such telescopes could detect all Type Ia supernovae out to at least the Virgo Group, providing a sample of many events per year.

Visions of Annihilation

Antimatter is being produced prodigiously in at least our own Galaxy. We will locate the source and understand how it produces this extraordinary material.

Our Universe is asymmetric. Most of the elements are made from normal matter ("baryons"). We know that antimatter exists in the Universe, but the amount and distribution remain uncharted. While the search for antimatter can be conducted with cosmic-ray and gamma-ray experiments, our Galaxy, and perhaps our Universe as a whole, is faintly glowing from annihilation of a lightweight form of antimatter, the positron (or antielectron). In such an annihilation, an electron and its positron counterpart most often directly annihilate into two 511 keV photons. Positrons are formed by the decay of radioactive elements, or as products of cosmic-ray interactions. Large scale positron production is theoretically expected from black hole antimatter factories.

Low-resolution positron annihilation maps of the Milky Way made by the Compton Gamma-Ray Observatory reveal recognizable features from the disk and inner bulge of our Galaxy, as well as evidence for emission concentrated at the center. The origin of these positrons is unclear, but radioactivity is a likely source. The maps show that positrons are distributed on a Galaxy-wide scale, but the pattern does not match that of any stellar component. Emission from compact sources could be highly transient, indicating that it may be dominated by a few compact sources, such as the mysteriously quiescent black hole at the center.

We look ahead to building new low-energy gamma-ray telescopes designed specifically to search for annihilation radiation. With vastly higher spatial resolution and sensi-

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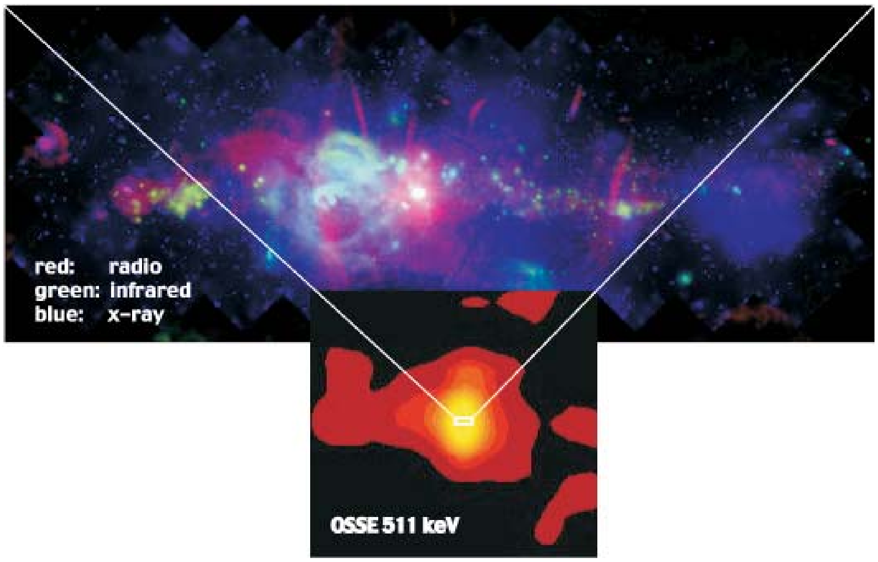
Searching for sources of antimatter in a galactic forest . . .



The image of 511 keV radiation from the Compton Gamma Ray Observatory is shown in the lower image and covers about 10 degrees of the sky around our Galactic Center. This is the highest resolution positron annihilation image available. At top is the wealth of structure in the very center of this region as seen in three different parts of the spectrum. This montage illustrates our need for much more detailed images from new generation gamma ray telescopes to identify the sites and sources of antimatter in the inner galaxy.

tivity than the Compton Observatory, such telescopes can reveal discrete sites of positron production in our own Galaxy and measure the production rates in other nearby galaxies. Observing the center of our Galaxy will establish whether a burst of star formation there is responsible for driving a superwind laden with positrons and newly synthesized material.

The Mystery of the Missing Matter

According to the best cosmological models, the total mass of the Universe (inferred from its gravitational force) appears to vastly exceed the mass of matter we directly observe. Estimates of the atomic (or "baryonic") mass of the Universe based on measured primordial ratios of hydrogen, helium, and deuterium can be made. These estimates still exceed the amount that we can actually see in stars and interstellar gas by a factor of ten, suggesting that a large component of normal matter is hidden in some way. But the gravitational mass of the Universe is much larger still, implying that much of the mass of it is not even in the form of atoms or their nuclear constituents. This "non-baryonic" matter would neither emit nor absorb light of any form and would reveal its presence only through gravity. Determining the nature of this non-baryonic dark matter is one of the central goals of modern physics and astronomy.

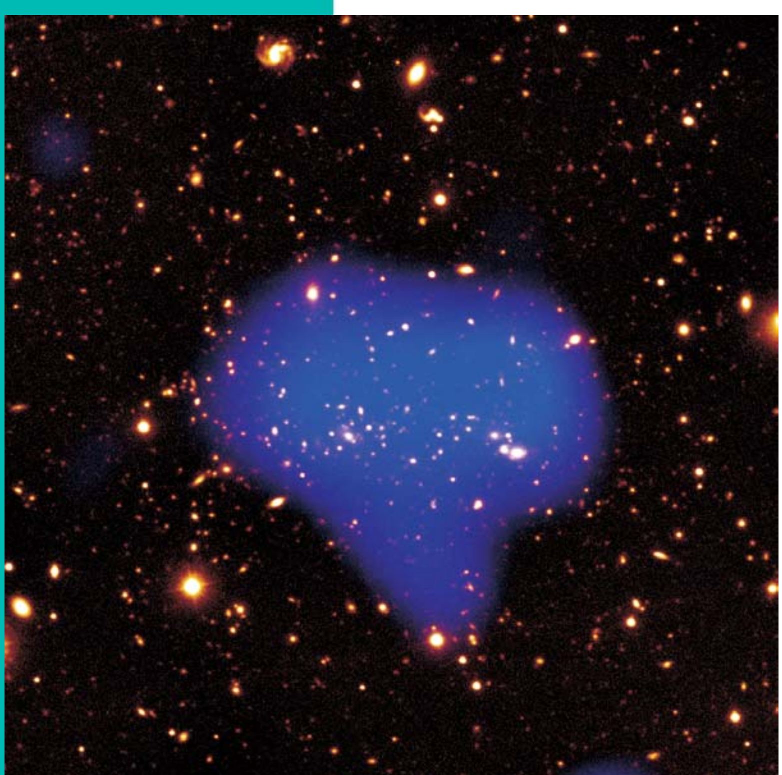
To keep their stars and hot gas from flying away, we infer that galaxies must be surrounded by halos of non-baryonic dark matter that provide additional gravitational attraction. Elliptical galaxies contain hot X-ray emitting gas that extends well beyond where we can see stars. By mapping this hot gas, which has been one focus of X-ray missions such as Chandra, XMM-Newton, and soon Astro-E2, we can develop a reliable model of the whole galaxy, showing where the dark matter lurks. Constellation-X will give a dynamical handle on the problem. Gravitational lensing provides yet another probe of dark matter.

New generation telescopes will be able to locate and assay both the baryonic and non-baryonic components of the missing matter, answering a longstanding problem with profound cosmological ramifications.

The missing baryonic matter is also important and elusive. Although some could be hidden from us in collapsed gas clouds or cold stars too dim to see, most is now believed to lie between the galaxies in the form of very tenuous and nearly invisible clouds of gas. Some may be associated with galaxies themselves, and some may follow the intergalactic web defined by non-baryonic matter. We want to find this missing matter to understand why so little of it was used to build stars and galaxies. By 2010, surveys will have outlined the distribution of luminous baryonic matter in and around galaxies in fine detail, but the intergalactic component will still be largely unexplored.

An efficient way to locate missing baryonic matter in the darkness of intergalactic space is to look for absorption of light from distant quasars. The Lyman α line is an exquisitely sensitive probe for cold hydrogen gas. If the baryonic dark matter is mainly primordial, such an ultraviolet detection strategy would be the only option. If the gas is hot and chemically enriched, then Constellation-X and large next-generation X-ray and ultraviolet telescopes will be able to see absorption lines from heavier elements. These efforts are difficult and just beginning on HST, FUSE, and Chandra. Constellation-X and new generation ultraviolet and X-ray telescopes will be needed to complete the task.

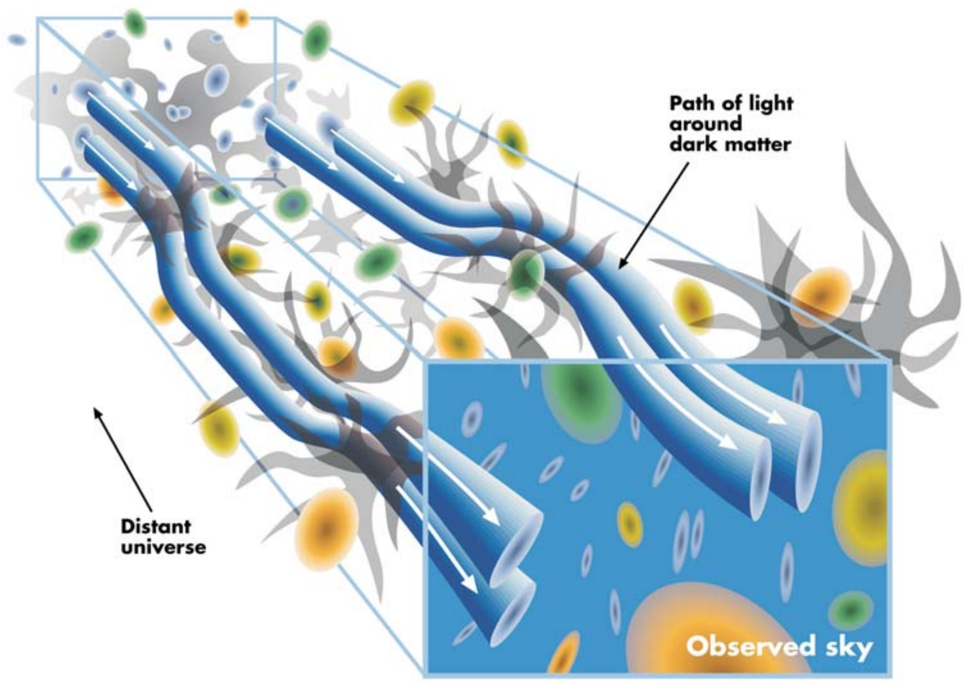
The fluctuations of the cosmic microwave background radiation are a powerful tool for assessing the total mass content of the Universe. First detected by the COBE a decade ago, these fluctuations have a scale size that will be characterized by the recently launched Wilkinson Microwave Anisotropy Probe (WMAP). ESA's future Planck mission will extend this to smaller scales and look for polarization signatures. The most important fluctuations are on scales of arcminutes, so it is essential to map the distribution of dark matter on a comparable scale. The *Beyond Einstein* program includes an Inflation Probe that will measure the polarization of this background. This polarization will reveal gravitational lensing by intervening mat-



Making missing matter appear . . .

The NGC 2300 group of galaxies contains a large reservoir of million-degree gas glowing in X rays. A false-color X-ray image of the hot gas (blue cloud) taken by ROSAT is superimposed here on an optical picture of the galaxy group. Gravity from the luminous parts of the galaxies alone is not enough to keep the gas in its place. There must be large quantities of dark matter whose gravity is preventing the gas from escaping.

Warped images from a clumpy Universe . . .



Light rays from distant galaxies travel a tortuous path through a Universe filled with a web of clustering dark matter. Every bend in the path of a bundle of light from a distant galaxy stretches its apparent image. The orientation of the resulting elliptical images of galaxies contains information on the size and mass of the gravitational lenses distributed over the light path.

ter, light or dark.

Once we understand the missing baryonic matter, we will have the first glimpses into the role that it plays in the evolution of our Universe.

Bullets of the Cosmos

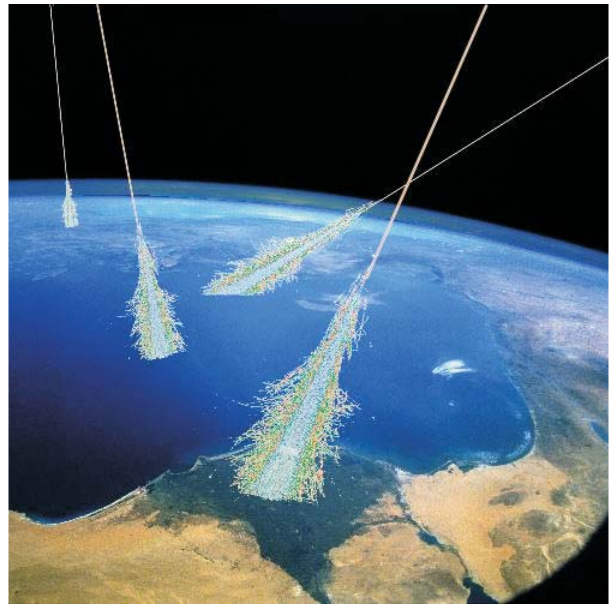
The origin of cosmic rays is a 90-year-old mystery. Most of these high energy nuclei are thought to be hurled at us by supernova shock fronts, perhaps from collisions with dust grains. Future measurements of the abundances of trace elements in cosmic rays can determine the nature of their sources and the time between the elements' creation and acceleration.

The distribution of cosmic-ray energies is remarkable in that it is almost a constant power law over at least 13 decades in energy. A small steepening, or “knee,” in the power law near 10^{15} eV is thought to represent the limit to energies achievable by supernova shock acceleration. A mission designed to measure the composition of these cosmic rays will explore their connection to supernovae by identifying these high energy nuclei.

At higher energies, the mystery deepens. In fact, we have detected cosmic rays up to about 10^{20} eV, where individual atomic particles have the energy of a well-hit baseball! About the only conceivable sources for these particles are galactic nuclei, giant extraga-

Cosmic rays are a window into how nature can channel enormous power into individual atomic nuclei. New observatories will reveal how our Universe is able to act as an extreme particle accelerator, the power of which is unapproachable on Earth.

lactic double radio sources, or the mysterious sources that give rise to gamma-ray bursts. Scattering off cosmic background photons should make the Universe fairly opaque to these highest-energy particles, so they must come from nearby sources. It has been suggested that the highest-energy particles could come from the annihilation of topological defects formed in the early Universe. The detection rate of these particles is so low that we see too few to describe their properties well. The DOE/NSF/UNESCO Pierro Auger Observatory now under construction is the next step in understanding these exceedingly rare but energetic particles. Results from it will inform the design of space instruments capable of monitoring still larger areas of the Earth's atmosphere for the showers these rare particles produce, to determine their energy spectrum and source directions.



Simulations of particle showers produced by 10^{20} eV cosmic rays in the Earth's atmosphere.

active galactic nuclei

dusty galaxies

supernovae